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TECHNOLOGY FOR SUBSYSTEMS OF SPACE-BASED PLANT GROWTH FACILITIES

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ABSTRACT

Technologies for different subsystems of space-based plant growth facilities are being developed at the Wisconsin Center for Space Automation and Robotics, a NASA Center for the Commercial Development of Space (CCDS). These include concepts for water and nutrient delivery, for nutrient composition control, and for irradiation. Effort is being concentrated on these subsystems because available technologies can not be effectively utilized for space applications.

WATER AND NUTRIENT DELIVERY SUBSYSTEM

Water and nutrient delivery to plant roots under microgravity conditions is a major concern in the development of a space-based plant growth facility. A concept for utilizing porous stainless steel tubes is being developed to accomplish this task. This concept was evolved from a membrane concept proposed by others (1) which was felt to have several limitations because it did not involve the use of a matrix and it had a limited period of usefulness.

The concept under development includes the use of a non-organic rooting medium in contact with the porous stainless steel tubes. The nutrient solution is circulated through the cavity of the porous tubes under negative pressure. The nutrient solution moves through the porous wall of the tube and into small pores of the rooting medium by capillary action (adhesion and cohesion of the water molecules). The larger pores in the rooting medium remain filled with air, thereby providing a non-saturated environment that is highly desirable for effective plant root functioning. Since the nutrient solution is contained by negative pressure and capillary forces, the liquid cannot escape into the atmosphere of a space vehicle in a microgravity environment. Thus, the proposed concept provides water and nutrients to plants while meeting three significant requirements for a space-based water and nutrient delivery subsystem for a microgravity environment: [1] provide a non-saturated matrix for plant roots, [2] prevent the escape of the liquid from the root zone to the atmosphere, and [3] allow the tubes and rooting medium to be easily cleaned and reused so that no consumables are involved in repeated growth cycles.

Three models of this concept have been constructed or are nearing completion. Each of these models consist of an array of porous stainless steel tubes (outside diameter of 1.04 cm and an inside diameter of 0.68 cm). The tubes have a pore size of 20 μm and a porosity of 50 percent. The tube size, porosity and pore size do not appear to be critical and were selected for convenience. The pore size has an upper limit that is related to the negative pressure under which the solution can be circulated through the tube cavity without drawing air into the tubes. The tube arrays are connected at each end by manifolds so as to provide a uniform solution flow through each of the tubes in the array.

A proof-of-concept model was constructed to provide preliminary information and experience for the construction of a more complete engineering model. The proof-of-concept model consisted of 10 porous tubes, spaced on 2.5 cm centers and connected to manifolds at both ends.

This provided a plant growing area 47 cm long, 28 cm wide, and 3 cm deep. The nutrient solution was circulated through the porous tubes under a negative pressure of -490 Pa (5 cm H_20). A flush cycle of -195 Pa (2 cm H_2O) for 1/2 hr each day was imposed to prevent salt accumulation on the surface of the rooting medium. A flow rate of approximately 125 ml per minute was maintained through the porous tube array. Lettuce plants were grown for 28 days and development of these plants was compared with those grown using a standard controlled environment procedure developed for base-line plant growth research (2).

Table 1 shows a comparison of the characteristics of lettuce plants grown in the porous tube nutrient solution delivery model with those grown with the base-line growing procedure. Plant characteristics were essentially equivalent. It does not appear to have been demonstrated that other concepts proposed for providing water and nutrients to plants under microgravity conditions have supported plant growth at equivalent rates. Figure 1 shows a comparison of lettuce plants grown under the two water and nutrient supply methods. Figure 2 shows the root development of lettuce plants grown with the porous tube delivery method. The general root development and distribution indicate that the rooting medium provided a favorable rooting environment that supported the high growth rates of the lettuce plants.

A more complex engineering model has been designed and it's construction recently completed. This model has 20 porous tubes 52 cm long and provides a growing area of 2700 cm^2. The depth of the rooting zone can be adjusted to a maximum depth of 15 cm to accommodate different types of plants. Operation of the unit is controlled by a microprocessor. Pressure sensors and flow meters at various sites in the flow path will permit continuous monitoring of the units operation. Sensors for conductivity, pH, temperature, and humidity are also included for monitoring these parameters during the course of an experiment.

A miniature model of the porous tube nutrient delivery system has also been constructed. This model is designed to replace the existing plant growth cells in the NASA flight-approved plant growth unit for the STS middeck locker. This model consists of 4 rooting zone trays each with a single porous tube and having a dimension of 20 cm long, 4.5 cm wide, and 3.5 cm deep. This unit would accommodate small plants proposed for microgravity research in the space biology program.

Future activity will be directed toward evaluation of the engineering model to define the optimum operational parameters of the porous tube water and nutrient delivery concept and to determine growth and productivity characteristics of various CELSS candidate species in this system.

Another activity initiated this year involves the development of a flight experiment to validate the porous tube delivery concept in microgravity. A flight experiment has been proposed and currently is manifested for inclusion in the US Microgravity Laboratory I (USML-1) mission scheduled for March 1992. The experimental goal is to evaluate the rate of capillary movement of water into and out of a matrix using a porous tube based water delivery system and to determine the capability of maintaining this matrix in a non-saturated condition under microgravity conditions.

Data collected from this experiment would not only be useful in defining the water and nutrient delivery requirements for plants growing in microgravity, but also provide information pertinent to the behavior of liquid/gas systems in microgravity. Such systems involve a number of space applications. A diagram of the flight experiment hardware is shown in Figure 3.

USE OF ION EXCHANGE MATERIALS FOR CONTROLLING CHEMICAL COMPOSITION OF NUTRIENT SOLUTION

Plants require that the solution surrounding roots contain specific ions within a certain range of concentrations depending on the nutrient ion and plant species. As the plant uptake of the nutrient ion proceeds, the solution around the roots becomes increasingly depleted. If no mechanism is provided for replenishing the nutrient ions, the solution soon becomes exhausted and plant growth stops.

At present, nutrient solutions balance is maintained by analyzing the solution and providing supplementation when the specific nutrients are depleted. However, accurate analysis of nutrient concentrations in space is fraught with problems. Certain nutrient analysis devices have been proposed for possible use in a CELSS (3). Of these, ion chromatography and specific ion detectors appear to have the best potential for continuous, or near continuous monitoring of ion levels in the nutrient solution. Unfortunately, ion chromatography requires relatively sophisticated equipment and has not been perfected for all nutrient ions. Specific ion probes require frequent calibration and replacement to provide continuous operation and again are available for only a limiteo number of nutrient ions. Thus, there remains a need to develop procedures for controlling nutrient concentration that can be automated and require little or no maintenance.

A concept based on utilizing ion exchange materials for controlling the chemical composition of the nutrient solution has been proposed. Five ion exchange materials, provide control of the 13 essential elements absorbed by plant roots and also control pH. These ion exchange materials maintain both the appropriate ion ratios and the concentrations required for plant growth.

Figure 4 shows a diagram of the components involved in the unit for controlling the chemical composition of a nutrient solution. Table 2 provides a listing of the ion activities controlled by each of the ion exchange materials. The conductivity sensor detects changes in ionic strength of the nutrient solution resulting from nutrient ion uptake by the plants. The pressure sensor detects changes in solution volume resulting from water transpired from plant surfaces. As these changes are detected, a control interface activates pumps to add stock nutrient solutions and water to maintain the ionic strength and volume of the nutrient solution.

Initial evaluations of the ion exchange materials have shown that the ion activities were effectively maintained with the exception of the phosphate ion, which was maintained at a level lower than desired. Additional work is underway to more clearly define the procedure for loading phosphorous onto the ion exchange materials.

Future activity will be directed toward obtaining the documentation required to define the procedures for loading the ion exchange materials so that the desired ion activities are maintained in the nutrient solution. This will be followed by confirmation that the ion exchange materials can effectively supply the proper ratio of nutrient ions required for plant growth and development. This portion of the program will utilize the engineering model of the Water and Nutrient Delivery Subsystem as described in the previous section.

IRRADIATION SUBSYSTEM

We have begun to study the potential of light emitting diodes (LED's) as photosynthetic light sources for plants (4). These devices have potential for use in space because they are solid state and consequently do not contain a gas-filled or vacuum bulb or tube. They also have the potential of greater photon efficiency than presently available lamps.

LEDs consist of a diode encased in transparent material as shown in Figure 5. The diode chip can be made of different materials so that varied wavelengths can be generated. A chip commonly utilized in high output diode construction is of gallium aluminum arsenide and produces a red light output between 620 and 680 nm as shown in Figure 6. This output closely matches the wavelengths of photons that provide maximum photosynthetic efficiency for plants, and is useful for plant growth systems. We are devoting efforts to the identification of LEDs with a spectral output in other regions required for plant growth. Currently, LEDs that emit in the visible region between 500 and 600 nm and in the far-red region between 700 and 760 nm are readily available. LEDs that emit in the blue spectral region (between 400 and 500 nm) are not readily available and have insufficient output. However, several companies are working to improve the output of these LEDs.

The potential efficiency of the LED chip for generating useful photons per watt of electricity is greater than the efficiency of presently available lamps. However, large losses can occur in passage of the photons from the chip through the transparent casing, resulting in an electrical efficiency that is rather low. Recent developments in LED technology have resulted in devices with an electrical efficiency similar to fluorescent lamps but less than for high intensity discharge lamps.

The capability of high frequency pulsing of LEDs (high nanosecond or low microsecond range) provides the possibility of obtaining significant gains in efficiency of irradiation for plants. These gains will be very large if the on-time and off-time duration of the electric power pulse can be synchronized to the time constants involved in the primary photochemical photon capture by the chlorophyll molecule, and the time constants for the enzymatic reactions of the photosynthetic process. If these photobiological processes can be synchronized, then the on-time of the LED array could be only 25% or less. Under such conditions the electrical efficiency of an LED array would be significantly better than any electric lighting system currently available for plant lighting. In addition, pulsing of the LEDs permits the LEDs to be driven at electric power levels significantly in excess of those permitted if the LEDs are driven in a continuous duty mode.

We have constructed several small arrays, mounting the LEDs on 0.5 to 1.0 cm centers, and have obtained irradiance levels of 700 μmol m^{-2} s^{-1} within a cm of the LEDs. We have initiated growth studies using an array consisting of red emitting LED's and supplemented the irradiation with blue fluorescent bulbs to provide 90% of the photons from the LED's and 10% of the photons from the fluorescent lamp. Growth of 'Grand Rapids' lettuce seedlings utilizing this irradiation has been similar to growth with cool white fluorescent lamps mounted to provide a similar photon level at seedling height.

Future activity will be concentrated on developing arrays with the most efficient LEDs available, utilizing the required balance of different wavelengths to obtain normal plant development. A number of LED manufacturers have introduced new products that exhibit improved performance characteristics and these new devices will need to be evaluated and incorporated into effective units.

REFERENCES

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Table 1. Growth characteristics of lettuce plants grown in the porous tube nutrient delivery system compared to plants grown in peat-vermiculite and watered with nutrient solution several times daily.

Treatment	Fresh weight (g±sd)	Dry weight (g±sd)	# Leaves (>1cm)	Length 5th leaf (cm±sd)	Width 5th leaf (cm±sd)
Porous Tube Nutrient Delivery System	45.3±4.0	2.59±0.26	12.2±0.7	14.6±0.8	15.4±1.0
Peat-Vermiculite Watered Daily With Nutrient Solution†	50.8±7.6	2.57±0.38	14.0±1.2	15.2±0.8	15.4±1.2

†Using procedure described in P.A. Hammer, T.W. Tibbitts, R.W. Langhans, and J.C. McFarlane 1978. Base-line growth studies of 'Grand Rapids' lettuce in controlled environments J. Amer. Soc. Hon. Sc. 103 649-655.

Table 2. Specific ion activities controlled by each of the ion exchange materials proposed for the nutrient control subsystem of a space-based growth unit.

	ANION EXCHANGE RESIN	BORON RESIN	CHELATING RESIN	WEAK ACID RESIN	ZEOLITE
pH				■	■
NO_3^-	■	■			
SO_4^{2-}	■	■			
$H_2PO_4^-$	■	■			■
K^+			■	■	■
Mg^{2+}			■	■	■
Ca^{2+}			■	■	■
Mn^{2+}			■	■	■
Zn^{2+}			■	■	■
Fe^{2+}					■
Cu^{2+}			■	■	■
B		■			
Na			■	■	■
Cl	■	■			

Figure 1. Comparison of lettuce plants grown in the porous tube nutrient delivery system and in peat-vermiculite watered automatically with nutrient solution 6 times daily.

Figure 2. Root development of lettuce plants grown with the porous tube nutrient delivery method.

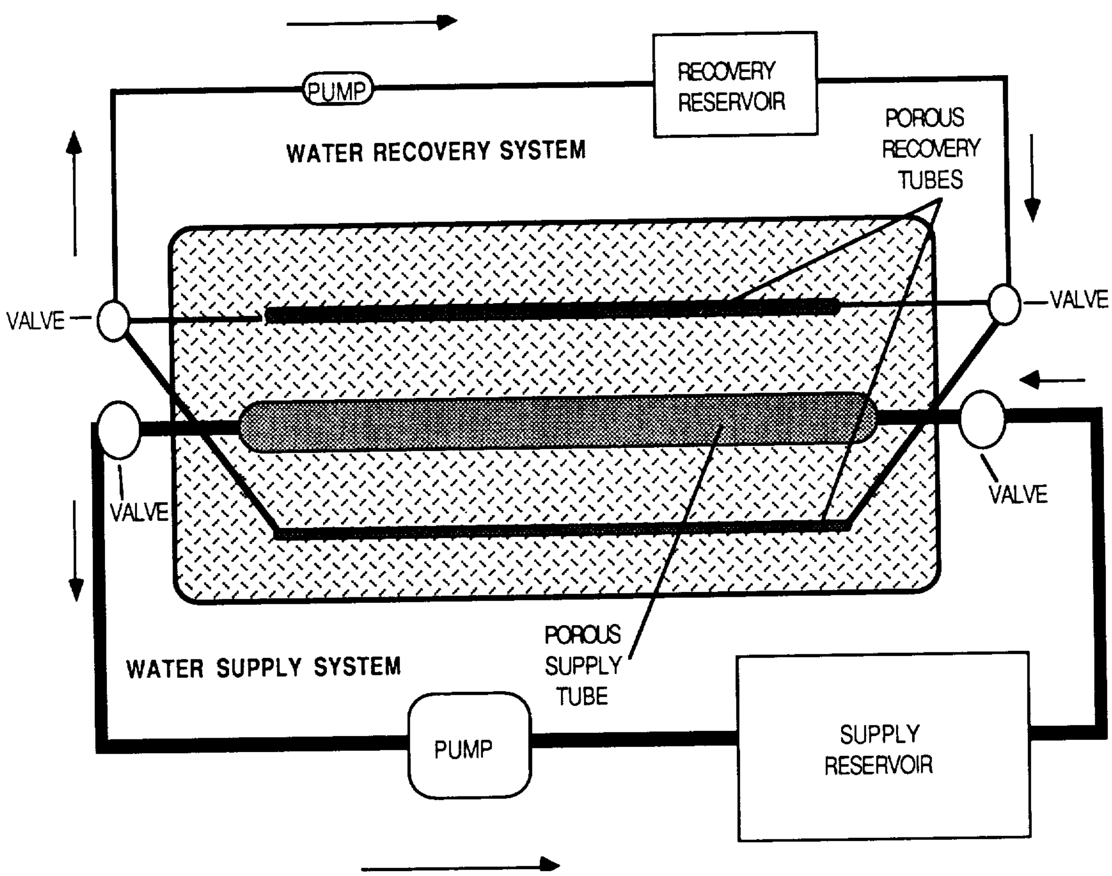

Figure 3. Diagram of hardware for flight experiment proposed to validate the porous tube nutrient delivery concept in microgravity.

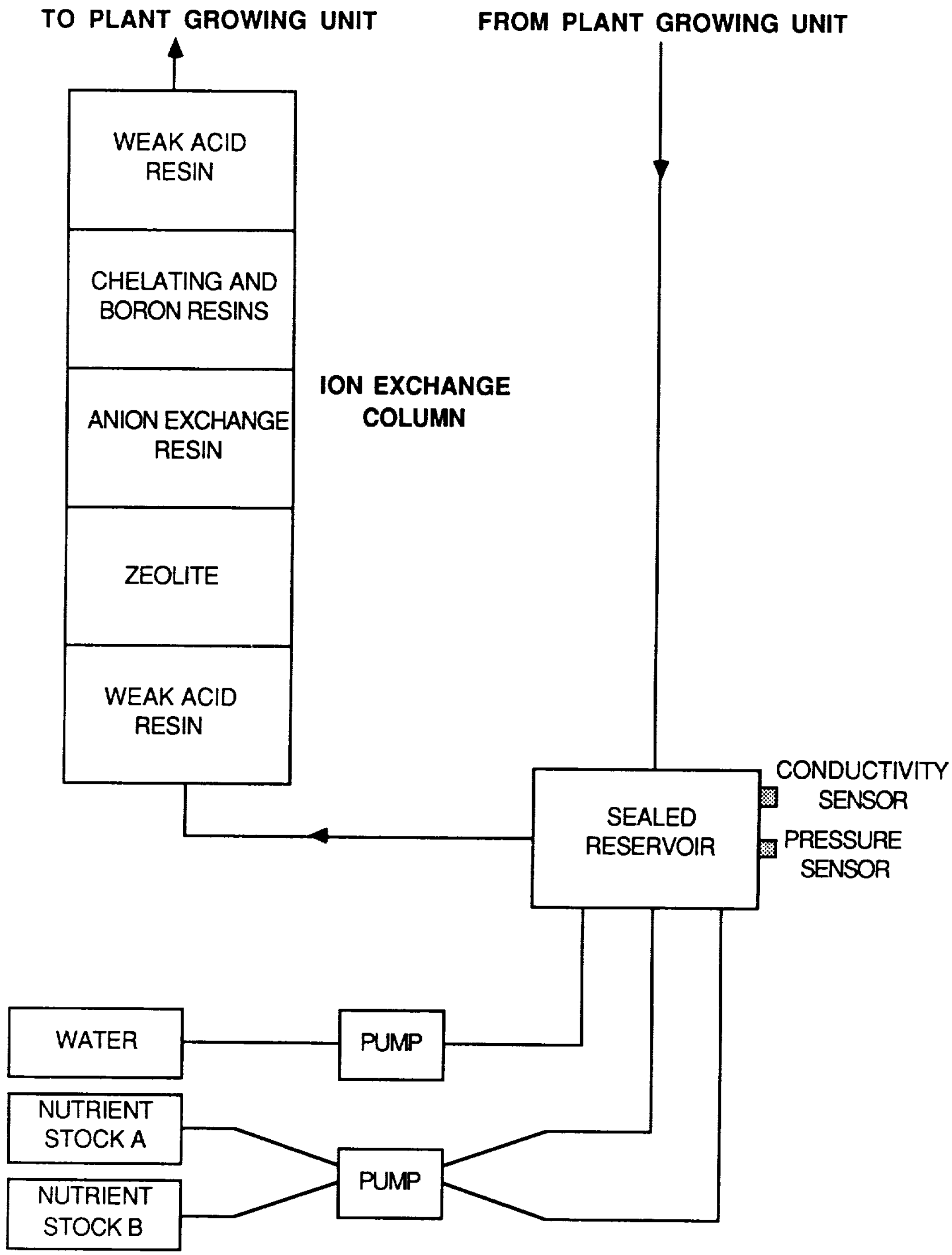

Figure 4. Diagram of the components involved in the unit for controlling the chemical composition of a nutrient solution.

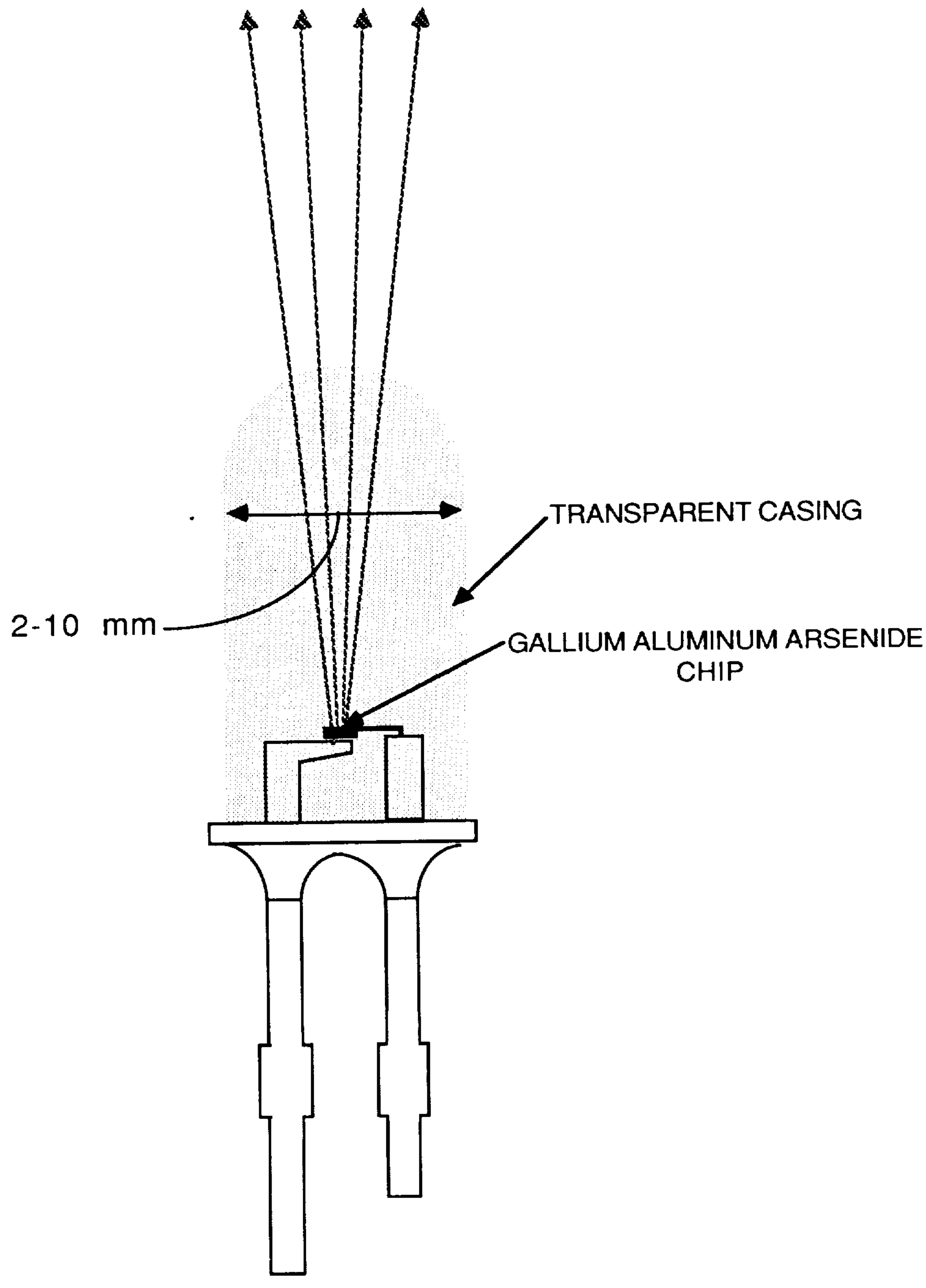

Figure 5. Diagram of a light emitting diode (LED).

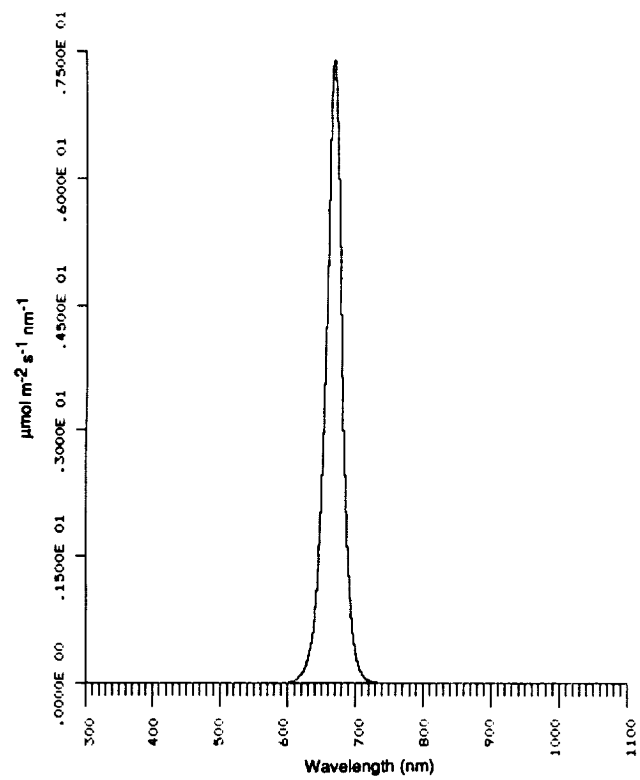

Figure 6. Relative emission of red light emitting LED.